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Numerical Study on the Imbalanced Flue Gas Temperature at Boiler Rear Pass Area of a Tangential-Fired Coal Power Plant

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Abstract This work presents the numerical study on the boiler temperature stability on a tangentially-fired 700MW coal power plant. The prime objective of the project is to identify the causes of imbalance flue gas temperature at boiler rear pass and to recommend the appropriate solutions to the problem. In order to achieve the objective, technical analysis utilizing the Computational Fluid Dynamics (CFD) simulation techniques was undertaken to simulate the combustion process, the combustion gas flow pattern and temperature distributions inside the boiler. The effects that were investigated were the effect of change in nozzle tilt angle and the effect of combustion using different coal types. The results of the baseline case indicate that the flow inside the furnace is very complex with intense mixing. The flow is highly swirling in anti-clockwise direction and the pattern persists until the exit of the boiler. Even with the design settings, the temperature distribution prior to the entry to the superheater is not symmetrical. The results show that that the uneven temperature distribution at upper furnace elevation exists regardless of the type of fuel used. It is suggested that the high gas temperature at furnace rear pass could be alleviated by operating at low tilt angle of the burner nozzle.

Keywords Numerical study, Temperature stability, Coal, Rear pass area, Tilt angle

1. Introduction

Steam generator plays an important element in most of the thermal power plant in the world today. The generation of steam in boiler normally requires huge amount of heat which is produced by burning fossil fuel. With the recent trend in the increase of fossil fuel price in the world, careful steps are taken by most of the boiler operators to optimize the use of these fuels and to find alternatives that could replace the fossil fuel. Despite some advancement made in the use of alternative energy source, e.g. renewable energy, it cannot totally replace the fact that the use of fossil fuel still can be considered significant at least in a few decades to come. In the open literatures, works on the study of combustion behaviour inside a boiler furnace were abundance. They can be broken down into several classifications in terms of the objectives such as to investigate the NOx emission e.g. [1–4], general combustion behaviour inside pilot or full scale furnace e.g. [5–9], investigation on the effect of boiler operating parameters e.g. [10, 11], CFD study to investigate the formation of fouling and slagging in furnace [12] and etc. However, the majority of these works concentrated on pilot scale or full scale boilers utilizing coal as the main source of fuel. Research on coal combustion in boiler furnace becomes the central attention among the scientist working in similar field probably due to the complexity of the combustion behaviour of the fuel that requires detail understanding on the processes and mechanism during the combustion. In addition, more attentions were given to the coal combustion study as compared to other fuel was due to the maximum utilization of coal in most of the countries around the world. This leads to very little attention given towards the study of other combustion in boiler furnace firing different fuel such as light and heavy fuel oil as well as natural gas. Tangential fired boiler is widely adopted by most of the boiler operators due to its many advantages especially when large capacity boiler is desirable. Among the most distinct advantages of this type of boiler is the ability to distribute heat evenly throughout the water wall. Despite this advantage, the existence of residual swirl in tangential-type boiler has created problem and if this problem is ignored, it could lead to the build-up of thermal stress in particular on the upper furnace which in turn, could cause boiler tube failure.

Effort to study the flow characteristics in particular the temperature imbalance in tangential fired furnace has been

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carried out many years ago but little progress was made in understanding this mechanism. This is especially true when the boiler is oil or gas-fired at which the average combustion gas temperature is higher than those of coal-fired boiler. Nevertheless, the earlier works carried-out by a few workers have opened-up wide opportunity for others to further investigate the phenomenon deemed to exist in almost all tangential fired furnace [13–16]. The imbalance temperature carried away to rear pass of the boiler has tremendous effect on the structural integrity of the boiler tubes and the boiler efficiency. The main culprit for the unbalance temperature at rear pass was predicted to be the burner angle setting. This paper investigates the phenomenon of the rear pass temperature profile with design and off-design conditions. Then, the solution to the current rear pass temperature problem is addressed.

1.1. Brief Description of the Boiler under Study

The 700MW boiler is shown in Fig. 1.

The power plant (3x700 MW) boilers are of sub-critical pressure, single reheat and controlled circulation type. Each boiler is fired with pulverised coal to produce steam for the continuous generation of 700 MW(e). The boilers are designed to fire coals within the bituminous rank.

The combustion circuit consists of a single furnace, with direct tangential firing and balanced draught. The firing equipment consists of (i) four elevations, (16) of, remote controlled fuel oil burners equipped with high energy ignitors, used to start-up the boiler and to support combustion of the pulverised coal at low firing rates. The capacity of oil burners is 40% of the Boiler Maximum Continuous Rate (BMCR), (ii) seven elevations, (28) of, coal burners located just above or below a fuel oil burner. The capacity of coal burners is 100% BMCR when firing coal within the design range. All the burners are located in the furnace corners (tangential firing).

The PC burners, the oil burners and the air nozzles are arranged in vertical layers. Each PC burner consists of an individual chamber connected to the PC pipe. All the burners and air nozzles can be tilted in the same time to raise and lower the “fire ball” in the furnace, to control the heat absorbed in the walls and in the radiant elements.

1.2. Problem Statement and Scope of Study

A reheater is a component of a coal fired power plant boiler which is responsible to reheat the steam known as cold reheat which is exiting the high pressure turbine. After being reheated, it is sent back to the second steam turbine. This reheater has boiler tubes placed in panels. While this process is going on, it was identified that there are uneven temperature distribution in the re-heater. This uneven temperature distribution can cause heat to be concentrated only on a certain region at the boiler tubes causing the tube to have temperature differences. When the temperatures are different along the tubes, it will cause irregular expansion processes which will lead to cracking in the boiler tubes of the reheater. Crack in boiler tubes will reduce the efficiency of the boiler system.

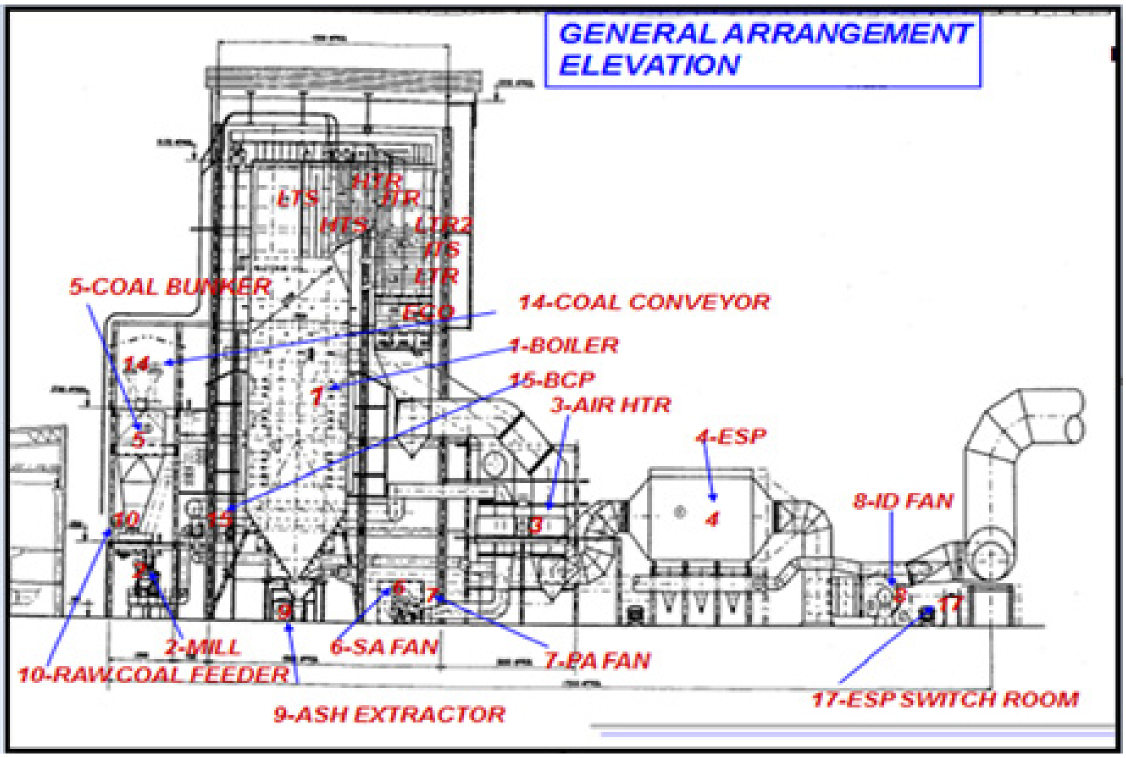

Figure 1. 700MW boiler general arrangement

The purpose of this project is to find a solution to reduce the uneven temperature distributions in the left and right-hand side of the reheater of a 700 MW boiler. The fluid that was being studied in this project was the flue gas. Flue gas or also known as combustion exhaust gas which is exiting to the atmosphere via a flue, which is a pipe or channel for conveying exhaust gases from a furnace, boiler or steam generator. Its composition usually consists of mostly nitrogen derived from the combustion of air, carbon dioxide, and water vapour as well as excess oxygen. It further contains a small percentage of a number of pollutants, such as particulate matter (like soot), carbon monoxide, nitrogen oxides, and sulphur oxides. The first CFD simulation was done for the existing plant operation in terms of the fuel and air flow configurations by using 3-dimensional CFD simulation. Once the simulation for the existing plant operation was done, then it was followed by testing on a few boiler parameters such as the effect of tilt angle on temperature distribution inside the furnace. Data from both the simulations was recorded and compared with the measured data.

The results gained in this investigation are useful to gain insight into the behaviour of combustion temperature and velocity in particular the formation of un-even gas temperature at the upper furnace. The optimum operating condition to alleviate the problem of un-even and excessive gas temperature at furnace rear pass was also be determined based on the extensive simulations on boiler tilt angles.

2. Methodology

2.1. Model Development

The boiler was modelled based on the detail manufacturer's drawing provided by the operator. Some simplifications were made on a few components of the furnace where detail dimensions were absent. In this study, detail dimension of the coal burners were not taken into account since detail flow study within and close to the burner regions were not needed. On top of that, the contour of water wall was assumed to be flat but in reality, the water wall consists of an array of horizontal pipes with complex surface curvature. The simplifications on complex geometry were necessary to avoid complex meshing which could cause divergence in the solution. These simplifications were applied to extreme regions with minor assumptions where the flow properties are not critical. This would not affect the final solutions of the flow and combustion characteristics in the furnace as the ultimate aim of this work is to predict the combustion gas flow and temperature profile at the boiler rear pass.

The 3D view diagram of the furnace is illustrated in Figure 2.

The furnace adopts tangential firing system at which an imaginary fireball is formed at the furnace centre. The furnace can be divided into four distinctive regions namely superheater/reheater, windbox, bottom ash hopper and rear pass regions. Coal and air are injected into the furnace through the windbox, which consists of several injection ports inclusive of the over-fire air at the topmost elevation. Detail flow and combustion characteristics are critical in this region and therefore, higher mesh concentration was applied to accurately resolve the flow field. Another important region that needs to be taken into account is the superheater and reheater regions which are located at the furnace top.

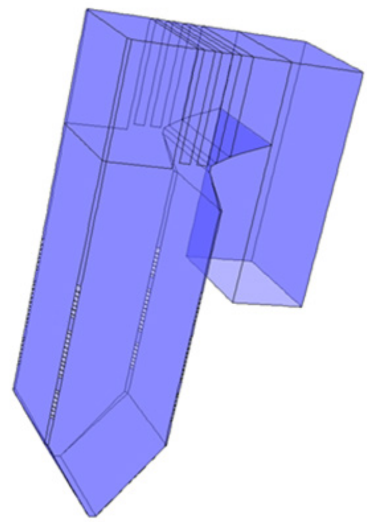

Figure 2. 3D view of the furnace model

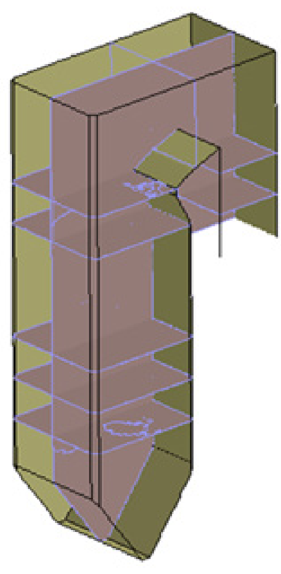

Figure 3. Planes at different x, y and z-direction for analysis

The model was developed such that the combustion gas flow terminates downstream of the rear pass to account for heat transfer in the superheater and reheater regions. This is located after the rear pass of the furnace. There were a total of 28 coal burners evenly distributed at 7 elevations in each corner. However, during normal operation, only 24 burners were used whereby the topmost burners are turned off. The coal is fed into different burner elevations from 6 mills which is available during normal operation, i.e. each mill provides uniform pulverized coal at to 4 burners in one elevation. In addition to coal burners and air nozzles, fuel oil burners are also present in the windbox region. The use of oil fuel is however limited to start-up sequence and during emergency situation when the coal supply is disrupted. In this work, the fuel oil burners were not modelled since only the coal combustion case was considered for investigation. For the purpose of analysis, several planes are created at different elevation in x, y and z-directions and these planes are shown in Figure 3.

2.2. Mesh Generation

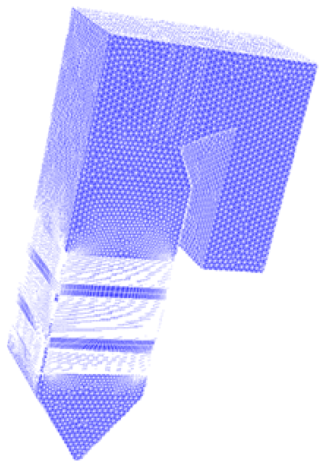

Figure 4. Mesh scheme of the furnace

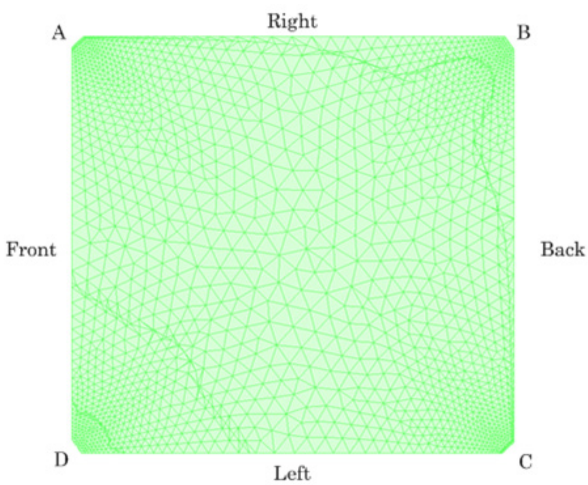

Figure 5. Detail mesh at coal injection plane

Generating a good mesh for flow and combustion calculation is extremely important to ensure sufficient solution accuracy. A combination of structured and unstructured grid was adopted in this investigation and this is shown in Figure 4. Higher mesh concentration was applied in the windbox region where fuel and air are injected for combustion, creating imaginary fireball at furnace centre that distribute heat evenly throughout the water walls. Due to its tangential firing system, intense swirl was anticipated at the furnace centre, thus careful attention was given towards the mesh scheme to resolve the swirl flows. Figure 5 shows the mesh scheme at the coal injection plane with high mesh concentration applied near the coal injection points. For the purpose of analysis, the four injection corners were named as A, B, C and D while the front, rear, left and right furnace sides were also labelled in the figure.

The boundary condition was set according the actual operating conditions of the furnace. The information was extracted from operating conditions for primary air, secondary air and coal injections and are summarized in Table 1.

Table 1. Summary of boundary conditions

Primary air	Secondary air	Coal flowrate
600 km^3/h	600 km3/h	360t/h

The coal inlet conditions were set as injection at which the particle was assumed to be combusting when the temperature exceeded the vaporization temperature of coal particle. The coal diameter distribution was assumed to follow the Rosin-Rammler distribution and the minimum and maximum diameters were estimated from published experimental data on coal combustion. The injection direction was specified according to the boiler design parameters and other injection properties were assumed to follow the actual operating conditions such as velocity, temperature, total flow rate, diameter, and spread diameter. The secondary air (SA) inlets were set as velocity inlet with the velocity of 30 m/s and temperature of 550 K. The pulverized coal (PC) inlets were set as velocity inlet with the velocity of 80 m/s and temperature of 300 K. The outlet of the furnace was specified as pressure outlet with backflow total temperature of 550 K. The outlet pressure was set to 0 to indicate that the system pressure at the outlet will be the operating pressure. The thermal conditions of the furnace wall were set as temperature with the temperature of 1,000K and internal emissivity of 0.7. The calculations were executed until approximately reasonable residual error was satisfied. To take into account the viscous effect resulted from high Reynolds number flow, the standard k-ε model was used as the closure to turbulence Reynolds equation. To resolve the flow field, SIMPLE method was employed with Lagrangian particle trajectory to track the coal particle. In order to account for the effects of turbulence on the particle trajectories in combustion model, stochastic tracking model were used in which three trajectory calculations were performed to include turbulent velocity fluctuations into the particle force balances. As the coal travels and interacts with the gas, the coal particles devolatilize and undergo char combustion, creating a source of fuel for reaction in gas phase. The two-competing-rates model was used to yield an expression for the devolatilization. The heterogenous combustion of char was calculated using kinetics/diffusion limited model. The interaction between the gas and particle phases was modelled by altering iterations between the flow calculation and the particle trajectory calculation, with 20 flow iterations per discrete phase iteration. Species and chemical reactions were modelled using the mixture-fraction/probability density function (PDF) approach and the full equilibrium chemistry, where the turbulence-chemistry interaction was modelled using a double delta PDF.

3. Results and Discussion

3.1. Temperature Profiles at Furnace Rear Pass

In order to specifically investigate the detail of temperature distribution at furnace rear pass, plots of temperature between the left and right hand side of the furnace were generated. Figure 6 shows the gas temperature distribution at furnace rear pass for different tilt angles. The general trend of temperature profile for all tilt angles shows similar pattern. It is clear that the right hand side shows higher gas temperature as compared to the left hand side with approximate difference of 100-150ºC. The highest temperature magnitude is given by tilt +30º while the lowest gas temperature is given by negative tilts (in this case -20º).

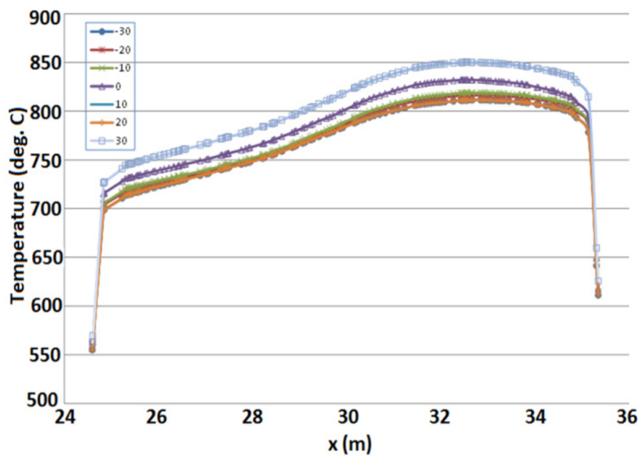

Figure 6. Temperature distribution at furnace rear pass (from left to right sides)

3.2. Rear Pass Temperature Profile at Different Tilt Angles

In order to investigate the temperature profile details at the boiler rear pass, plots of temperature against distance is made in the regions. Three lines are created at the rear pass where the plot was made and this is shown in Figure 7. The three lines were named line-back, line-mid and line-front to indicate the locations where the temperature plots were made respectively. The plots were made at constant furnace elevation (rear pass elevation) while variation was made along x (left to right) and z-axis (note: z-axis indicates the back, mid and front side of the furnace).

Based on the observation made on the boiler unit and 1 and 2, it was found that the existing behaviour shows higher rear pass temperature at both the left and right hand sides (LHS and RHS) of the furnace. However, the severity of excessive flue gas temperature was found to be extremely high on the RHS compared to the LHS. The gas temperature was found to exceed the maximum limit temperature set by the manufacturer. Prior to the simulation of combustion behaviour inside the furnace at different tilt angle, a test case simulation on the same furnace using different type of coal was also carried out to validate the findings made on site with regards to different gas temperature for different type of coal used. In this case, property of Kayan coal was used in the simulation for comparison with Adaro.

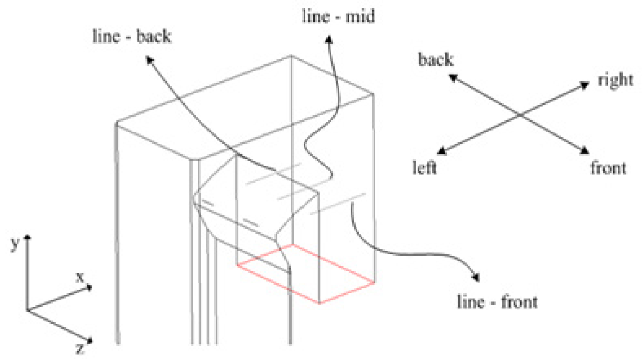

Figure 7. Schematic diagram of the location of line profile at boiler rear pass for analysis

The analysis for temperature profile was taken at furnace rear pass due to the fact that the only temperature information available for comparison was at this location. From the simulation, in overall, it is predicted that the gas temperature given by Kayan coal combustion is higher as compared to the Adaro coal combustion and the detail plot and comparison is shown in Figure 8. This is in agreement with the measure data taken at furnace rear pass as shown in Figure 9 and Figure 10.

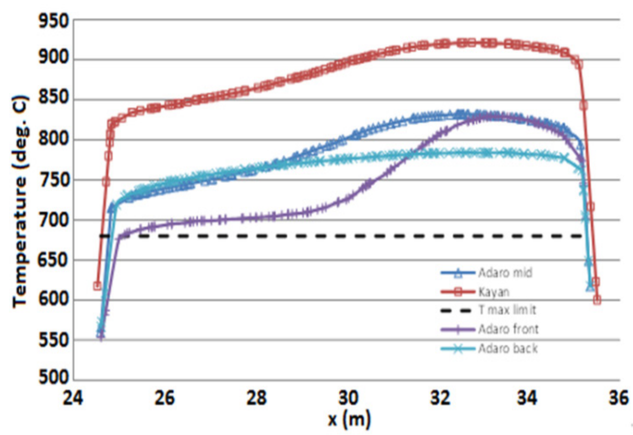

Figure 8. Temperature distribution at furnace rear pass for Adaro and Kayan coal combustion

However, the magnitude of flue gas temperature was predicted to be higher than the measured one and this can be attributed to the insufficient value set for heat absorption rate at the water wall. In addition, in the simulations, the platen superheaters and reheaters were not modelled to reduce the complexity of the calculated flow domain. Figure 11 shows the plot for gas temperature at furnace rear pass for three different locations namely back, front and middle (refer to Figure 7 for the location of plots in furnace the rear pass). The plot is taken at design tilt angle of 0 degree. From the plot, it shows similar trend compared to the measured data where the RHS shows higher gas temperature than the LHS. The approximate difference in gas temperature between the LHS and RHS also shows similar trend with the measured data of 100ºC.

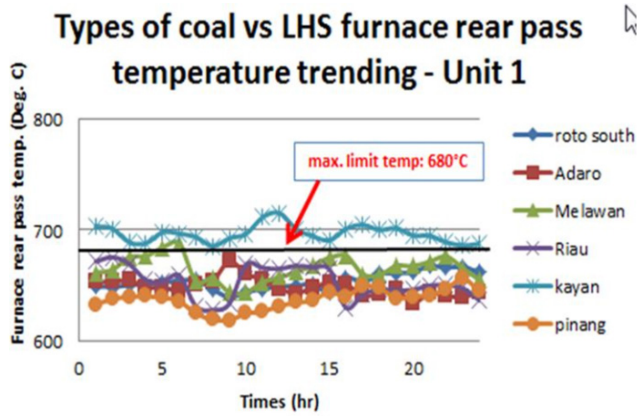

Figure 9. Gas temperature at LHS furnace rear pass temperature against time

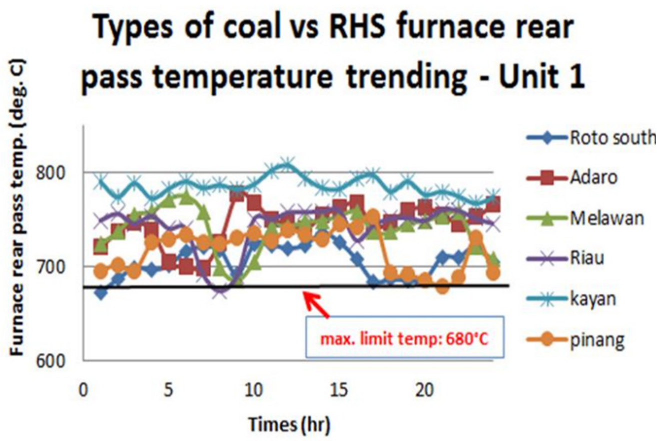

Figure 10. Gas temperature at RHS furnace rear pass temperature against time

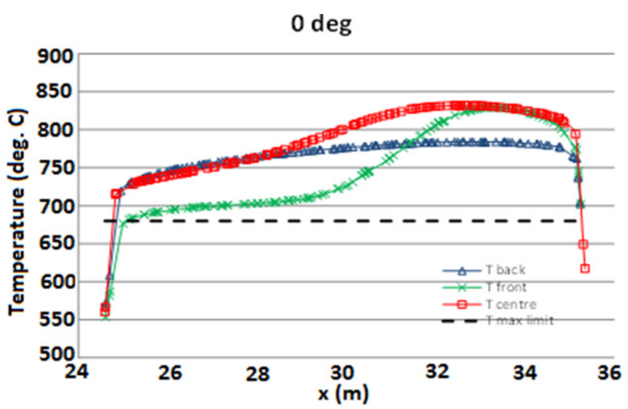

Figure 11. Temperature profile at furnace rear pass taken at centre, back and front boiler sides

4. Conclusions and Recommendations

Based on the simulation results obtained, the following conclusions can be withdrawn:

- Specifically, the trend shows that the furnace RHS temperature is always higher than LHS. However, the magnitude differs with tilt angle.
- The overall temperature magnitude predicted by the simulation show higher temperature magnitude compared to the measured data. This can be attributed to the simplification made to the simulation model which ignores the physical body of superheater and reheater platens at furnace top. However, in the simulation, it was assumed that the heat absorption rate of these platens are transferred to the heat rate by the water walls. This heat transfer rate was obtained based on trial and error due to insufficient data provided by the station. Despite the higher gas temperature predicted, the trend for all cases were found to be in good agreement with measure data.
- The flow inside the furnace is highly swirling due to the effect of tangential firing system, indicating good mixing of coal particles and air. The temperature distribution at main combustion zone (windbox region) is initially symmetry in shape and the formation of fireball is right at the centre of the furnace. As hot flue gas flows upwards, the symmetricity of the temperature distribution is slightly off-centred as the fireball location shifted upon passing the furnace nose at higher elevation. This causes the temperature difference between the left and right hand side of the furnace.
- The temperature difference, (ΔT) between the left and the right hand-side of the furnace was also found to differ as furnace elevation increases. For the baseline case (tilt at 0°), the ΔT is approximately 80°C between RHS and LHS. Other tilt angle conditions also give more or less similar temperature difference magnitude. The highest ΔT is recorded for tilt angle of +30° at approximately 100°C. Whereas, the lowest predicted at -20° tilt angle with ΔT magnitude of only 60°C. Based on the major findings obtained from the simulation and validated data by measurement taken on-site, it is recommended that the station operates at minimum tilt angle (preferably -20º) to reduce the gas temperature at furnace rear pass. Even though this method does not eliminate the temperature variation between the left and right side of the furnace, this setting is predicted to give the minimum gas temperature at furnace rear pass compared to other tilt angle setting.

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